Compression creep of ABS polymers

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Compression creep measurements on acrylonitrile–butadiene–styrene (ABS) polymers were conducted to compare with the results of the impression creep tests at similar stress levels and testing temperatures. The creep curves of ABS polymers obtained from the compression tests were similar to those from the impression tests, namely they all exhibited transient and steady-state stages. The stress and temperature dependences of the steady-state strain rate obtained from the compression tests were in general agreement with the corresponding quantities obtained from the impression tests at temperatures below 353 K; however, they deviated from each other at higher temperatures.

(Keywords: compression creep; ABS polymers; steady-state strain)

INTRODUCTION

Compression creep measurements on ABS polymers were carried out to compare with the results of the impression creep tests. Since polymer characteristics are sensitive to the manufacturing processes and thermomechanical treatments, materials supplied from different manufacturers may have different properties. For instance, the glass transition temperature is strongly affected by the molecular weight, additives and the degree of crosslinking[1]. The glass transition temperature of polystyrene used in the experiments of Andrews[2] was reported to be 356 K, which is 17 K lower than that used in Chang and Li's study[3]. Because we could not find any data in the literature for similar compositions, working temperatures and stresses to those used in our impression creep measurements, we had to perform our own experiments in compression in order to compare the results between the impression creep tests and conventional creep tests.

EXPERIMENTAL

Sample preparation

The ABS polymers used in this study were the same as those used in the impression creep measurements. Rods 80 mm in length and 3 mm in diameter were machined from the as-received plaques along the longest side and surface ground. Rod specimens with lengths ranging from 5 to 9 mm were prepared by cutting the long rods into pieces with a slow speed diamond saw. Different specimen lengths were needed to accommodate a variety of experimental conditions. For example, the longer specimens were good for low temperatures and low stress conditions because they facilitated a more accurate strain measurement. The shorter specimens were good for high temperatures and high stress conditions because buckling could be avoided during the test. After the cut, the two ends were finely polished to give parallel surfaces. The rods were annealed at 373 K for 3.5 h and then furnace cooled to room temperature to relieve stresses[4]. This method of sample preparation was time consuming in comparison with the method of sample preparation for the impression tests.

Apparatus

A constant load compression creep apparatus was built to conduct the creep measurements. A schematic diagram of the apparatus is given in *Figure 1*. Two ceramic cylinders with smooth ends were used as the top and bottom rams that compressed the specimen rod during the experiment. A stainless steel rod was used to join the top ram to a supporting plate. To achieve better central alignment, the stainless steel rod was surrounded by an 8 cm long cylinder with two concentric linear bearings. A guide rod parallel to the stainless steel rod was surrounded by another linear bearing through the supporting plate. The guide rod was needed to maintain the level and stability of the supporting plate and also to help in the alignment of the instrument. To reduce the moment generated from the loading and frictional forces between the stainless steel rod and the linear bearings, a loading disc with a short, slender cylinder in its centre was placed on the supporting plate. A predetermined weight was put on the loading disc to apply stress to the specimen.

Because the furnace was made of two pieces of heating element, each of which was fixed inside a metal case with the two metal cases joined together with two hinges, the furnace could be opened conveniently to replace the specimen. Two thermocouples, one close to the specimen and the other close to the heating element, were used for temperature measurement and control. The temperature fluctuation in the furnace was controlled to less than ± 1°C. The compressive displacement of the specimen was measured by a linear variable differential transformer (LVDT). The LVDT was enclosed inside a case and an adjustable screw was on the case bottom to slide the LVDT up and down to accommodate the different

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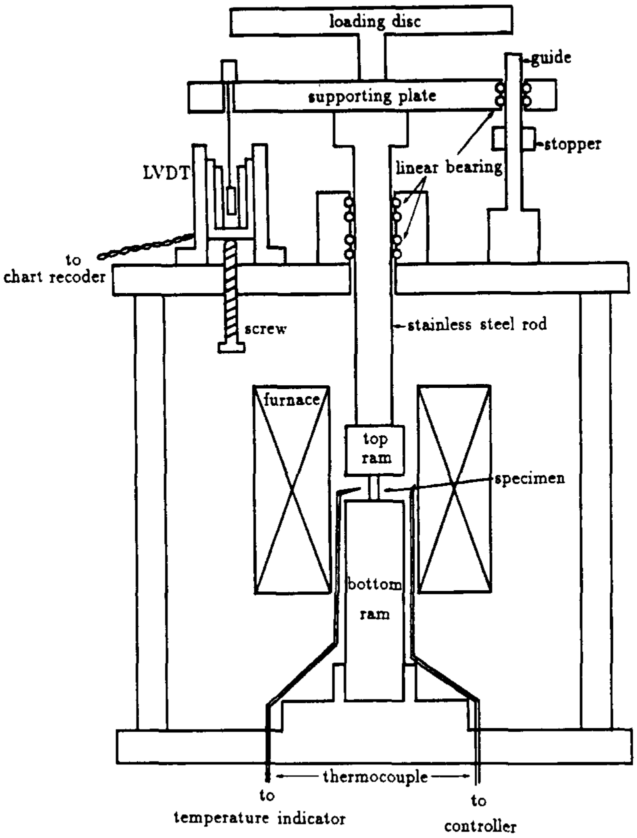

Figure 1 Schematic diagram of the compression creep apparatus

specimen lengths. The output signal from the LVDT was monitored by a chart recorder. The strain was calculated from the signal on the recording paper using the equation

$$\varepsilon = -\ln\left(\frac{l_0 - \Delta l}{l_0}\right) \tag{1}$$

where l_0 is the initial specimen length and Δl is the compressive displacement at time t.

During the experiment, Teflon tapes were put between the rams and the specimen as lubricant to reduce barrelling. However, some barrelling was observed when the strain was 5% or more.

Experimental procedure

The specimen rod was located along the central axis of the rams. A stopper attached to the guide was first used to lift the supporting plate before the temperature reached the desired value. After the temperature had been at the desired value for about 20 min to allow the apparatus to become thermally stabilized, the stopper was released and the predetermined dead load, which consisted of a number of steel blocks, was applied to the specimen. The experiment was terminated after a period of time when the steady-state stage was clearly shown on the recording paper. The strain was calculated from the signal on the recording paper.

RESULTS AND DISCUSSION

Creep curves: creep strain versus *time*

Typical creep strain *versus* time curves are shown in *Figure 2*. The strain rate decreases with time and reaches a steady state after an initial transient period. The curves resemble those obtained from the impression creep measurements. The steady-state strain rate increases with temperature and applied stress.

Stress dependence

The stress dependences of the steady-state strain rates for ABS-10, ABS-17 and ABS-25 (see the previous paper for a description of the samples) are plotted in *Figures 3–5*. The logarithm of the strain rate shows a linear relationship to the applied stress under the experimental conditions. The results are similar to those obtained from

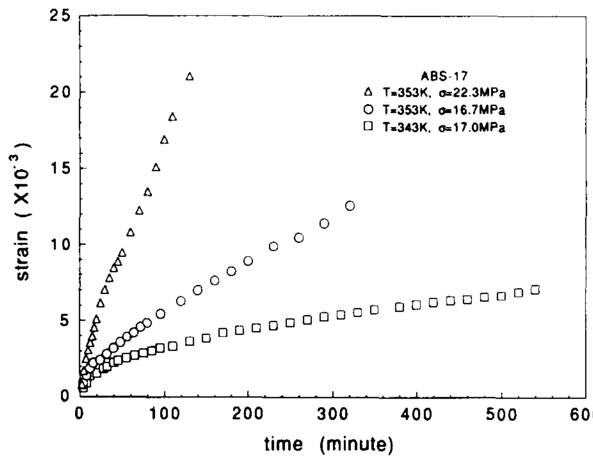

Figure 2 Typical creep strain *versus* time relationships for ABS polymers

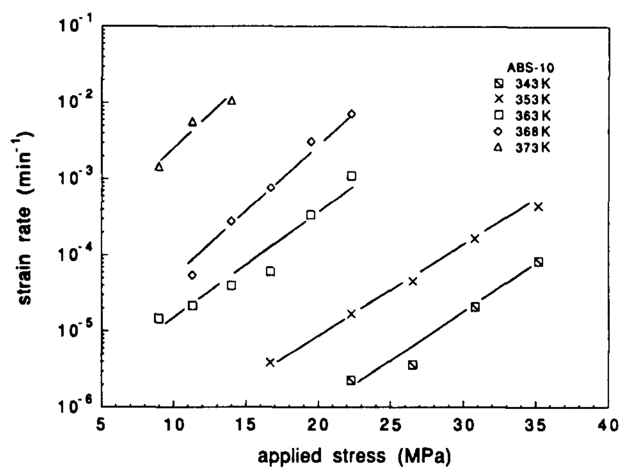

Figure 3 Stress dependence of the strain rate for ABS-10

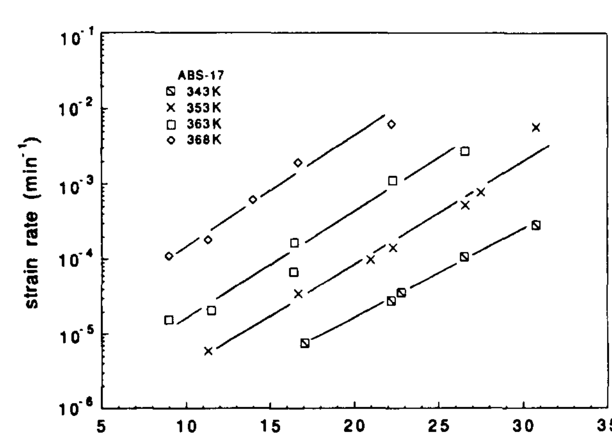

Figure 4 Stress dependence of the strain rate for ABS-17

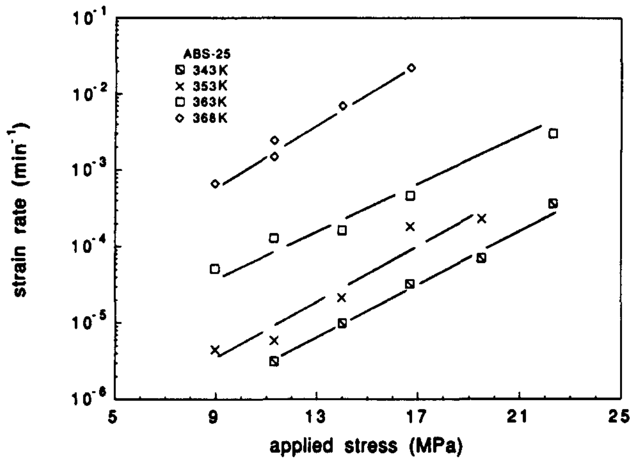

Figure 5 Stress dependence of the strain rate for ABS-25

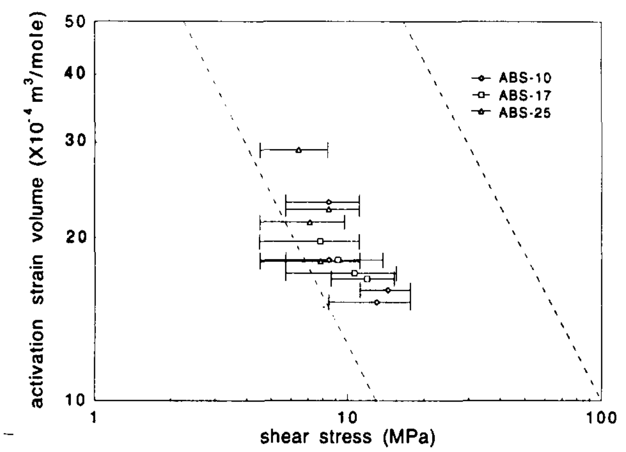

Figure 6 Double-logarithmic plot of the activation shear strain volume *versus* the shear stress for ABS polymers in the compression creep test

the impression creep measurements. The linearity between the logarithm of the steady-state strain rate and the stress implies that the reverse motion, which is opposite to the applied stress direction for the mobile flow units, can be neglected[5]. The deformation is not at a near-equilibrium state.

The activation shear strain volume (Ω), calculated from the slope, is given by

$$\Omega = -\left(\frac{\partial \Delta F}{\partial \tau}\right)_{T,P} = RT\left(\frac{\partial \ln \dot{\varepsilon}}{\partial \tau}\right)_{T,P} \quad (2)$$

where τ is the applied shear stress and is one-half of the applied normal stress, ΔF is the activation free energy, which is the energy difference between the normal state and the activated state of the flow unit, and $\dot{\varepsilon}$ is the strain rate. R, T and P have their usual meanings. The activation shear strain volume plotted against the applied shear stress is shown in *Figure 6* on a double-logarithmic scale. The data points are located close to the lower boundary of the general correlation for all materials[5], the upper and lower boundaries being shown by two parallel dashed lines. The data obtained from both impression creep and compression creep measurements are plotted together in *Figure 7*, in which the solid symbols represent the impression measurements and the open symbols represent the compression measurements. Generally, the results obtained from both methods are mixed together.

The average shear strain volume decreases with increasing shear stress and increases with increasing butadiene content. At the same shear stress level, the shear strain volume obtained from the compression test is slightly larger than that obtained from the impression test for the same polymer. Because the deformational behaviour of polymers is more sensitive to the applied stress than is that of metals[6], the difference in strain volume for a deformed polymer may reflect the difference in stress distribution in the specimen under the two testing methods.

Temperature dependence

The temperature dependences of the steady-state strain rates for the various polymers with different butadiene contents are presented in *Figures 8–10*. The activation enthalpies were calculated from the slopes of the plots of log (strain rate) against reciprocal absolute temperature. In general, the enthalpy is insensitive to the stress because the lines at different stress levels are approximately parallel. The activation enthalpy determined in the compression creep test has the same tendency as that determined from the impression creep test, as shown in *Figure 11*, namely that the activation enthalpy gradually

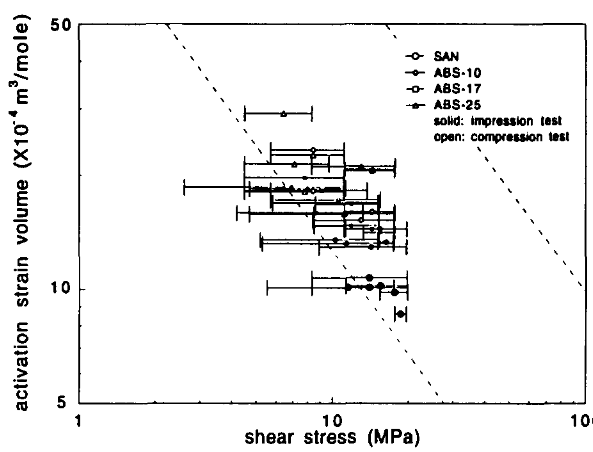

Figure 7 Comparison of the results for the activation shear strain volume obtained from the impression creep test (solid symbols) and the compression creep test (open symbols)

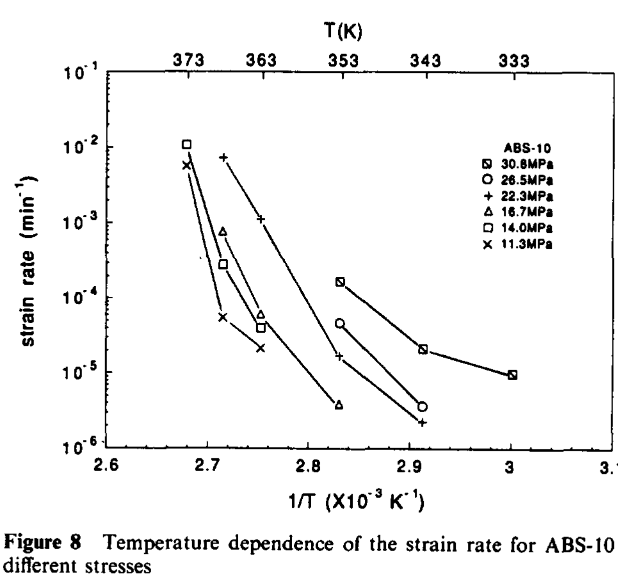

Figure 8 Temperature dependence of the strain rate for ABS-10 at different stresses

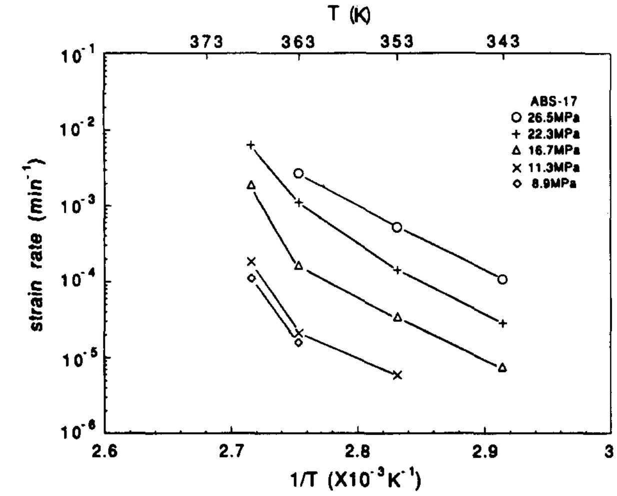

Figure 9 Temperature dependence of the strain rate for ABS-17 at different stresses

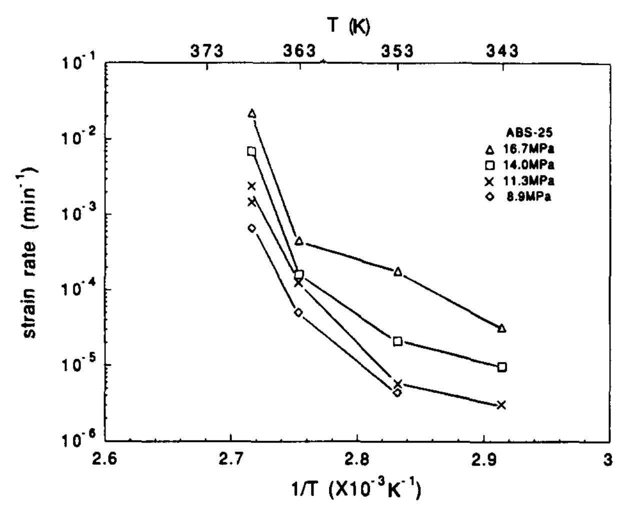

Figure 10 Temperature dependence of the strain rate for ABS-25 at different stresses

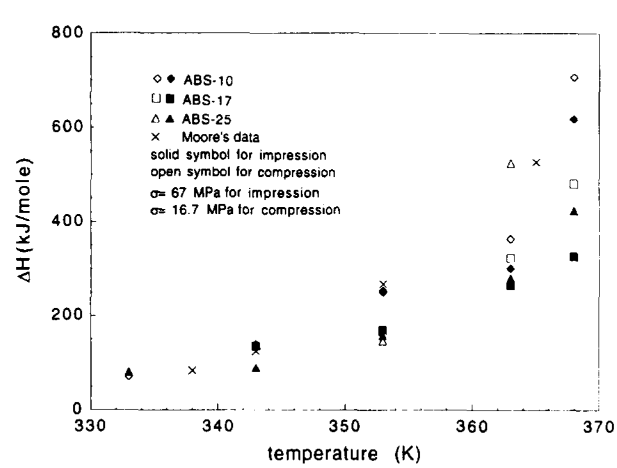

Figure 11 Comparison of the activation enthalpies obtained from the impression test and the compression test

increases with temperature below 350 K and then increases more rapidly when the temperature approaches the glass transition temperature. The activation enthalpies obtained by Moore and Gieniewski[7] are also included in the plot. When the temperature is below 353 K, the enthalpies obtained from impression, compression and tensile creep measurements are comparable to one another. However, when the temperature increases to over 353 K, the enthalpy obtained from the unidirectional creep tests is higher than that obtained from the impression creep tests.

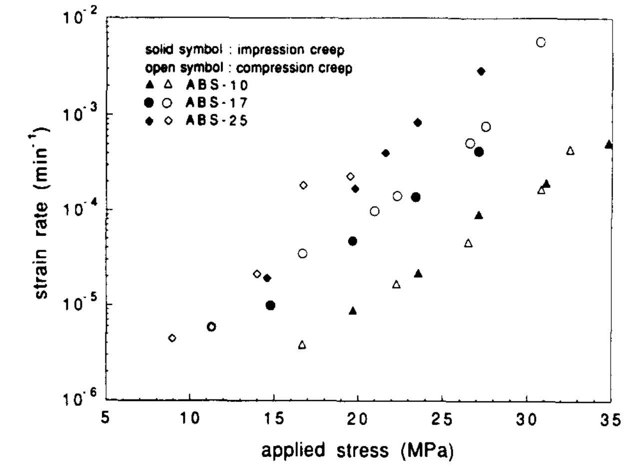

Figure 12 The stress conversion factor (3.4) brought the results obtained from the impression test closer to the results obtained from the compression test at 353 K. The strain rate in the impression test was the ratio of the impression velocity to the punch diameter

No data could be obtained from our compression creep measurements if the temperature was near the glass transition temperature because the polymers were too soft to handle and instantaneous barrelling upon loading could not be avoided. Therefore, another advantage of the impression creep test is in its ability to study the deformation kinetics at temperatures used for polymer shaping in a mould, which are higher than the glass transition temperature.

A comparison between impression and compression tests

The stresses applied in both impression and compression tests were correlated by plotting the logarithm of the equivalent strain rate *versus* the applied stress for three different polymers at 353 K, as shown in *Figure 12*. For the best correlation there was a factor of 3.4 between them, which is the ratio of hardness to compressive stress. The factors obtained in this study are not constant but increase with temperature. These factors are 3.4 for 343 and 353 K, 3.6 for 363 K and 4.1 for 368 K.

When the creep rate for the impression test is taken as the impression velocity divided by the punch diameter, the ratio of the punching stress to the creep stress used in the conventional uniaxial test for several materials is listed below for comparison. The ratio is 3.1 for succinonitrile[8], 3.4 for lead[9], 3.5 at 333 K increasing to 3.9 at 476 K for β-tin with a [110] orientation, 2.8 for β-tin with a [001] orientation[10], 6.7 for LiF[11] and about 10 for zinc[12].

The constraining effect of the undeformed material surrounding the deformation zone in the impression test may depend on many things, such as the available slip systems, the existence of flow units and their distribution inside the material, the average slip distance (or grain size in crystalline materials) and so on. In general, the ratio between hardness and compressive stress should be high if the constraining effect is severe and low if the constraining effect is slight. The penetration depth at high temperatures is usually larger than that at low temperatures. This may explain why the ratio increases with increasing temperature.

SUMMARY

1. The creep curves of ABS polymers obtained from the compression test were similar to those obtained from the impression test when the strains were less than 5%.
2. The logarithm of the strain rate showed a linear relationship to the applied stress. The activation shear strain volume increased with increasing butadiene content and with decreasing applied stress. The temperature did not have a strong influence on the activation shear strain volume.
3. The activation enthalpy increased gradually with temperature at temperatures below 353 K and then increased more rapidly with temperature above 353 K. The activation enthalpy was not influenced by the applied stress in the range studied.
4. The stress and temperature dependences of the steady-state strain rate obtained from the compression tests were in general agreement with the corresponding quantities obtained from the impression tests at temperatures below 353 K; however, they deviated from each other at temperatures higher than 363 K.
5. The ratio of hardness to compressive stress for the same strain rate increased with increasing temperature from 3.4 at 343 K to 4.1 at 368 K. It appeared that the constraining effect of the undeformed region surrounding the deformed region in the impression test became more severe at higher temperatures.

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